Final Report of AFOSR Project
”Study of Equatorial Ionospheric Irregularities with ROCSAT-1/IPEI Data for Assessment of Impacts on Communication/Navigation System (ⅠⅤ)”

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14. ABSTRACT
Monthly variation of global equatorial density irregularity distribution has been obtained with data taken by ROCSAT-1 at the 600 km topside ionosphere from March 1999 to June 2004 during high to moderate solar activity periods. This complete global longitudinal distribution of monthly equatorial density irregularity occurrence variation provides not only the best spatial/temporal distribution existed so far but also fills the large gap of irregularity distribution missing over some Pacific regions where few ground observation is available. The 5½-year result of the monthly occurrence pattern indicates a smooth variation across longitudes contrary to some beliefs that a drastic change in irregularity occurrence pattern can occur across some longitudes in the Pacific. Excellent agreement is noted for the current results with Aarons’ conjectured sketch of global scintillation occurrence distributions [1993]. Furthermore, the seasonal/longitudinal (s/l) variations of quiettime post-sunset vertical drift velocities are found to track closely with the s/l variations of irregularity occurrences except during the September equinox season. Linear regression analysis between the vertical drift velocity and the irregularity occurrence rate has been carried out to study the correlation between the two in seasonal as well as longitudinal variation. The results indicate that the vertical drift velocities at three different longitude regions of different magnetic declinations have good correlations with irregularity occurrences for all seasons. This implies that the vertical drift velocity alone can drive the occurrences of equatorial density irregularities in proportion even though its effectiveness has longitudinal variation. The most effective longitude is in the South America-Atlantic region, while the worst one is in the Pacific region where some large perturbation seeds seem needed to assist the occurrences of irregularities.

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Executive Summary

Monthly variation of global equatorial density irregularity distribution has been obtained with data taken by ROCSAT-1 at the 600 km topside ionosphere from March 1999 to June 2004 during high to moderate solar activity periods. This complete global longitudinal distribution of monthly equatorial density irregularity occurrence variation provides not only the best spatial/temporal distribution existed so far but also fills the large gap of irregularity distribution missing over some Pacific regions where few ground observation is available. The 5½-year result of the monthly occurrence pattern indicates a smooth variation across longitudes contrary to some beliefs that a drastic change in irregularity occurrence pattern can occur across some longitudes in the Pacific. Excellent agreement is noted for the current results with Aarons' conjectured sketch of global scintillation occurrence distributions [1993]. Furthermore, the seasonal/longitudinal (s/l) variations of quiettime post-sunset vertical drift velocities are found to track closely with the s/l variations of irregularity occurrences except during the September equinox season. Linear regression analysis between the vertical drift velocity and the irregularity occurrence rate has been carried out to study the correlation between the two in seasonal as well as longitudinal variation. The results indicate that the vertical drift velocities at three different longitude regions of different magnetic declinations have good correlations with irregularity occurrences for all seasons. This implies that the vertical drift velocity alone can drive the occurrences of equatorial density irregularities in proportion even though its effectiveness has longitudinal variation. The most effective longitude is in the South America-Atlantic region, while the worst one is in the Pacific region where some large perturbation seeds seem needed to assist the occurrences of irregularities.

I. Interim Report Delivered on September 30, 2006

A. Comparison of the longitudinal variation in the monthly occurrence rate of density irregularities observed by ROCSAT-1 with past scintillation results of Aarons [1993].

The ROCSAT mission was conducted around the peak of solar cycle 23 from 1999 to 2000 when the solar activity varied from high to moderate. The daily solar flux index F10.7 is about 220 during the high solar activity year of 2001 and around 100 in the moderate year of 2003. However, the occurrences of density irregularities observed at topside ionosphere do not seem to vary dramatically as seen in the seasonal/ longitudinal (s/l) distribution shown in Figure 1. The s/l distribution indicates the persistence in the pattern of occurrence distribution. This implies that our understanding of the irregularity triggering seed distribution as well as the growth of the instability process has remained correct for the years of high and moderate solar activity years.

Data in Figure 1 is then re-plotted in monthly occurrence distribution at a longitude around the globe as shown in Figure 2. This figure is used to compare with available ground observations of density irregularity effects in radiowave scintillation experiment and equatorial spread-F (ESF) in ionosonde data. A study of global distribution of radiowave scintillation has been published in a report by Tsunoda [1985]. The report indicates that the irregularity is prone to occur at an equatorial region when the sunset terminator is aligned with the local magnetic field line. This conclusion creates the term of “ESF longitudes” in an “ESF season” at longitudes of large magnetic declination during a solstice season where the irregularities occurred very frequently. Later, Aarons in a review paper [1993] summarized the results from all the scintillation observations that the scintillation is definitely related to density irregularity. He then constructed a map of global distribution for scintillation occurrences. In the seven (7) longitude regions shown in his report, the monthly occurrence rate in a year is presented. Extracting the ROCSAT data shown in Figure 2, we construct a comparison result of Figure 3 to show the topside density irregularity occurrence pattern in comparison with Aarons’ scintillation data. Notice that Aarons’ original construction of monthly scintillation variation only shows the relative occurrence probability, while the

ROCSAT data gives the exact probability of irregularity occurrence rate. However, it is surprising to see that from limited data taken some 30 years ago, Aarons was able to construct a result that is verified by the current ROCSAT observations. This again shows the persistence of ESF occurrence distribution in past 30 years. Although small discrepancies are noted in Aarons' conjectured results in comparison with ROCSAT data, the over-all occurrence pattern remains similar. For example, the exact monthly occurrence variation has some shift of peak or minimum occurrence months. The most inconsistent example is seen at longitude of Kwajalein where the month of June has a maximum occurrence in the ROCSAT data but a minimum in Aarons' scintillation result. This discrepancy will be investigated further.

B. Initial study of new NCU-SCINDA data.

The AFRL's SCINDA-NCU station was set up in March, 2006. After that we have observed a couple good irregularity drift events as shown in Figure 4. Since then, no good drift event has been observed even though some scintillations have been noted in data. An example of such observation was carried out by detailed analysis. Figure 5 show this event of Aug 7 observation in which the full wave mode recorded data was available for detailed analysis. As noted in the first two panels in Figure 5, there are large scintillation S4 indices which indicated the existence of irregularities as observed by the two channels. However, no drift was seen for the irregularities as indicated in the bottom panel of the figure. Section of the data from the full wave mode taken at 120 Hz was studied with cross-correlation analysis. The result indicates that there is indeed no shift in data between the two channels (Figure 6). Although we have discussed such peculiar finding with Dr. Keith Groves at Hanscom AFRL, PI of SCINDA experiment, no definitive conclusion has been reached so far. The scintillation data will be further analyzed in more detail, including examining the spectra etc. to determine the nature of the fluctuating signals and hopefully gain better understanding of the phenomenon.

Since the FORMOSAT-3/COSMIC launch in April, 2006, we do not have any good coincident observations between SCINDA and FORMOSAT-3/COSMIC. The seemingly failed SCINDA experiment in observing good drift event could be one of the cause. We need more time to figure out what happens to SCINDA drift measurements before comparison with other data can be carried out.

II. Final Report Added on May 31, 2007

A. Provide the possible cause for large differences in the longitudinal variation of scintillation occurrence pattern.

A.1. Cross-Correlation Between Vertical Drift Velocities and Density Irregularity Occurrences

Quiet-time equatorial vertical drift velocities observed by ROCSAT-1 at 18-19 local time without concurrent density irregularity occurrences are studied with the seasonal/longitudinal (s/l) distribution of quite-time equatorial density irregularity occurrences before midnight to obtain the seasonal and longitudinal variations between the two variables. Figure 7 shows the two s/l distributions in comparison. Notice that the s/l distributions of the longitudinal variations of the vertical drift and irregularity occurrence rate during the two solstice seasons are similar, but they don't seem to follow each other in the two equinox seasons. The two variables are further studied with cross-correlation analyses, and the results for every season are shown in Figure 8.

The occurrence of equatorial density irregularities is closely related to the strength of post-sunset electric field that raises the post-sunset ionospheric height to become susceptible to the generalized gravitational Rayleigh-Taylor (R-T) instability. The electrodynamic process to generate the post-sunset eastward electric field is related to the flux-tube integrated Pedersen conductivity that is affected by the alignment of sunset terminal with the magnetic flux. Therefore, the magnetic declination plays an important role in determining the post-sunset electric field. We thus use symbols "+", "-", and "o" in Figure 8 to identify data points taken at longitudes of positive magnetic declination from 150° to 270°, at longitudes of negative declination from 270° through the prime meridian to 30°, and at longitudes with small, near-zero magnetic declination from 30° to 150°, respectively.

Different degree of correlation is noted between the vertical drift velocity and irregularity occurrence rate in different seasons. The December solstice season has the best correlation and the September equinox, the worst. A couple of points can be concluded from the results in Figure 8. First, an ionosphere with a larger vertical drift velocity can result in more frequent irregularity occurrences. This seems logical but also contradicts to a previous report of Fejer et al. [1999] in which they reported that the threshold of drift velocity to generate strong irregularities increases with solar flux. It is important to note that the current study is to correlate the s/l variation of background ionosphere condition with the probability distribution of s/l variation of irregularity occurrences in a statistical sense. No one-to-one causal relation between the vertical drift velocity and the subsequent irregularity occurrence is provided here, as was studied by Fejer et al. [1999]. To have a better statistics in Figures 7(a) and 7(b), the current report discards small solar activity variation effect for data taken during the periods of high to moderate solar activity years from 1999 to 2004. Our result indicates that as a large vertical drift velocity raises the post-sunset ionosphere higher, the ionosphere becomes more susceptible to the R-T instability process and a higher probability of observing irregularities is expected. Because of the complicated processes involved in the R-T instability process, whether one-to-one correlation exists between high vertical drift velocity and high irregularity occurrence is not studied in the current report.

Second, except for the result in September equinox where poor correlation appears, the linear regression indicates that a vertical drift velocity can result in irregularity occurrence in a linear fashion with a proportionality constant of about 15m/s in vertical drift velocity to 10% in occurrence probability. It should be noted that 10% of irregularity occurrence probability is rather high because the highest probability of irregularity occurrence per night is about 30% on the average. Thus when the post-sunset vertical drift velocity is only about 15 m/s we can expect a 30% chance of observing an irregularity occurrence if there is an irregularity occurrence. Furthermore, it is also noted in Figure 8 that many data points with "-" symbols lie on the upper side of the regression line. This indicates that high irregularity occurrences took place at longitudes of negative magnetic declinations. On the other hand, some larger vertical drift velocity also fails to drive a large irregularity occurrence rate and this is most noticeable during the September equinox. These data points are mostly identified with symbols "+" that took place at longitudes of positive magnetic declinations. Thus a new regression analysis using the longitudes of different magnetic declination as a reference is carried out to study the correlation between the vertical drift velocity and the irregularity occurrence. The result is shown in Figure 9. In the figure, we use the alphabetic letter to identify the observation made in the four seasons such as M for FMA months, J for MJJ and so on. From the regression fitted line, we note that it seems that data are scattered in such a way that there is no seasonal differences. Although the linear correlation seems improved, the proportionality between the vertical drift velocity and the irregularity occurrence rate drops somewhat in comparison with the better ones in Figure 8 such as in the December solstice and March equinox. This implies that the effectiveness of resulting in irregularity from purely the vertical drift velocity effect is good even though it needs somewhat higher vertical drift velocity to drive the irregularity occurrences. Therefore, some other factors seem missing to assist the occurrences of post-sunset irregularity besides the vertical drift velocity that sets up a favorable ionospheric condition for the R-T instability process. One of such factors is the seed perturbations to trigger instability. This is discussed in the next subsection.

A.2. Seed Perturbations of Irregularity Occurrences

The importance of seed perturbation to result in irregularity occurrences has been presented in many reports [e.g. Rottger, 1981; Huang and Kelley, 1996; McClure et al., 1998; Tsunoda, 2005]. In the report of McClure et al., the authors claimed that the post-sunset ionospheric seems to be always set from the pre-reversal enhancement to be in a favorable condition for the R-T instability process so that the final outcome of the s/l distribution of irregularity occurrence should be related to the s/l distribution of seed perturbation. They further indicated that the s/l distribution of the intertropical convergence zone (ITCZ) correlates well with the s/l distribution of irregularity occurrences. The current results of Figures 8 and 9 modify part of their claim and strengthen other part.

Result of Figure 9 indicates that the post-sunset ionospheric condition is not universally uniform in longitudes and the variation of vertical drift velocity can, in fact, support the irregularity occurrence probability in proportion. Thus the difference of the vertical drift velocity matters. If the result of Figure 9 alone is used to discuss the correlation between the vertical drift and the irregularity occurrence probability, one may conclude that the vertical drift velocity alone can adequately drive the irregularity occurrence. This then puts the current report at odds with the report of McClure et al [1998]. However, there is more information deduced from Figure 9. It also indicates that the post-sunset vertical drift velocity alone to drive the irregularity occurrence is very ineffective at longitudes between 150° and 270° in the eastern Pacific. This is clearly noticed from data of "+" symbols in Figure 8 for the correlation in the June solstice and September equinox seasons. This implies that seed perturbation relating to the irregularity instability process still counts and it is hard to come by in the eastern Pacific regions during these two seasons. Whether the s/l distribution of ITCZ alone can adequately provide seed perturbation to correlate with the s/l distribution of irregularity occurrences as was claimed in the report of McClure et al. is discussed further.

If the ITCZ can provide sufficient seed perturbation for the irregularity occurrence, it fails to indicate so in Figures 7(b) and 8 because high ITCZ activities have been reported by Waliser and Gautier [1993] (in their Figure 1) in the Pacific region during July and October months. The reason for the discrepancy that high activity in ITCZ fails to enhance the irregularity occurrence probability seems to lie in the fact that a high activity of ITCZ may not correspond to a high seed perturbation for the ionospheric instability process. One important factor for an atmospheric disturbance to become the perturbation seed in the bottomside ionosphere to excite the ionospheric instability process is that the tropospheric disturbance has to penetrate the tropopause to propagate upward to the upper atmosphere [Rottger, personal communication, 2007]. An existence of topographic feature could assist the atmospheric convection to penetrate the tropopause into the lower ionosphere. Thus a high activity in

ITCZ that fails to become good seed perturbation in the eastern Pacific region could be understood from the fact that there is no topographic feature to launch a deep atmospheric disturbance through the tropopause to the upper atmosphere. In addition, Figure 7(b) further indicates a contrastingly high irregularity occurrence in the longitude regions of negative magnetic declination from 270° through the prime median to 30° in almost all seasons even for small vertical drift velocities. A constant existence of seed perturbation induced by the topographic feature of the Andes mountain range in the South America could play an important. A prevailing zonal eastward wind across the Andes mountain range that exists at the boundary of ITCZ can generate many different kinds of mountain waves to result in deep atmospheric convection to have upward propagating gravity waves. These waves seem to penetrate the tropopause easily to serve as good perturbation seeds to excite the R-T instability in the lower ionosphere to result in large irregularity occurrences when ionosphere is susceptible to instability. These seed perturbations seem to extend their effects even during the June solstice season when the ionospheric boundary condition is not so favorable for the R-T instability process because of large angle alignment between the magnetic flux tube and the sunset terminal at these longitude sectors.

Therefore, the global s/l distribution of irregularity occurrence comes from the convolution of two distributions with gravity wave distribution representing the seed perturbation and with the vertical drift distribution representing the instability process [Rottger; 1981; McClure et al., 1998]. One should not expect that the s/l variation of either vertical drift velocity distribution or ITCZ distribution alone can completely represent the global s/l variation of irregularity distribution. However, our result indicates that, as the first approximation, global s/l variation of vertical drift velocity distribution is a better representation than the s/l variation of ITCZ distribution for the global irregularity distribution.

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Waliser, D. E. and C. Gautier, A satellite derived climatology of the ITCZ, J. Climate, 6, 2162-2174, 1993.

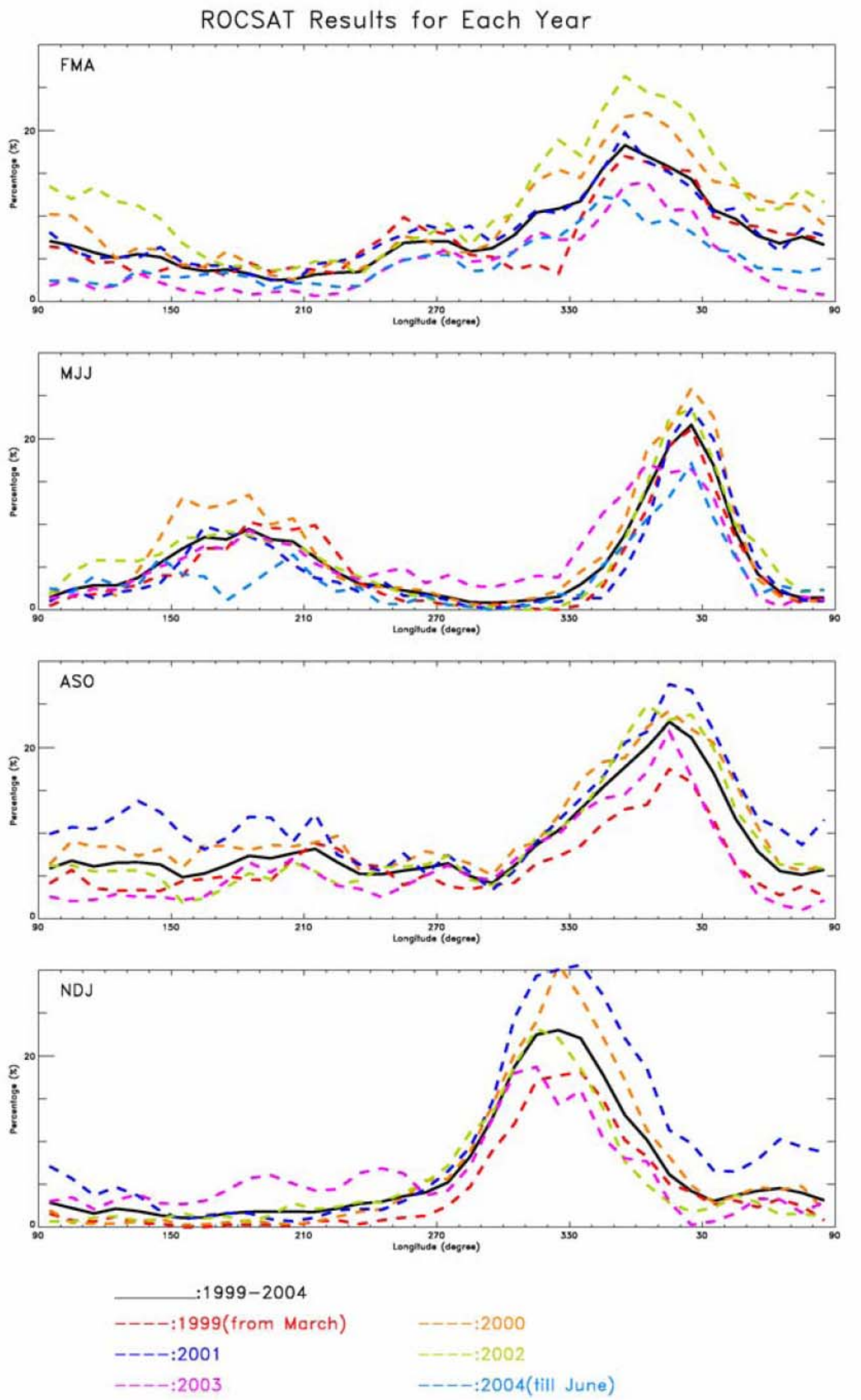


Fig.1. The yearly occurrence rate of density irregularities in seasonal/longitudinal distribution. The black line in each season is the 51/2-year averages of the occurrence rate.

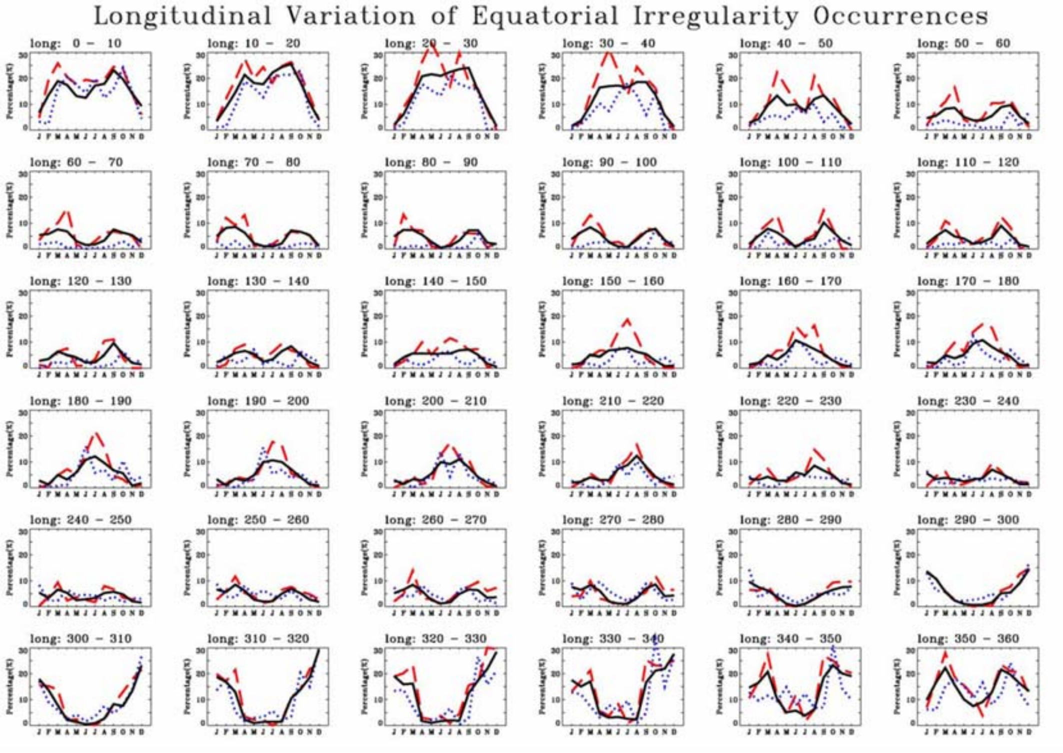
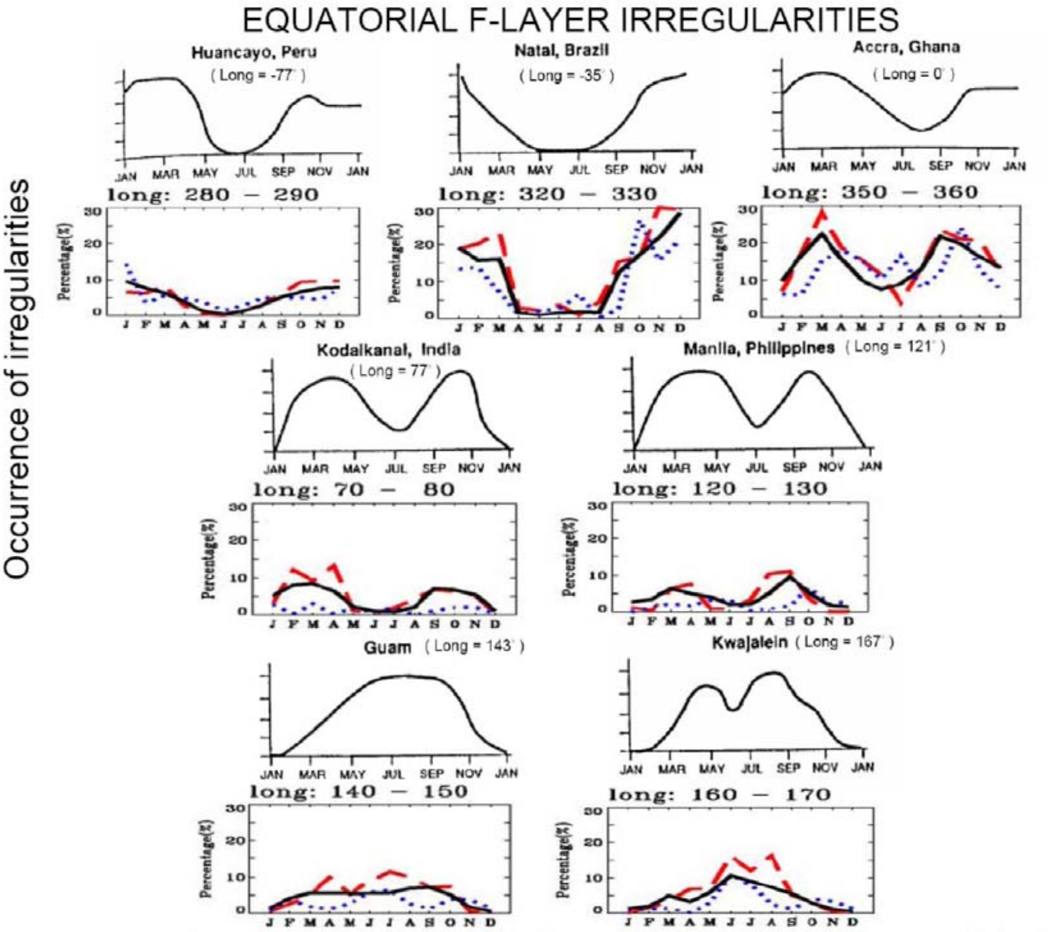


Fig.2. The global distribution of monthly occurrence rate of irregularities for 2001 (red dashed lines) and 2003 (red dotted lines). The black lines are the 51/2-year averages.



Comparison of ROCSAT observations with expected monthly occurrence pattern derived from scintillation data by Aarons [1993]

Fig.3. Predicted monthly occurrence rate of scintillation results from Aarons' paper [1993] against the ROCSAT observed density irregularity occurrence rate at the same longitudes.

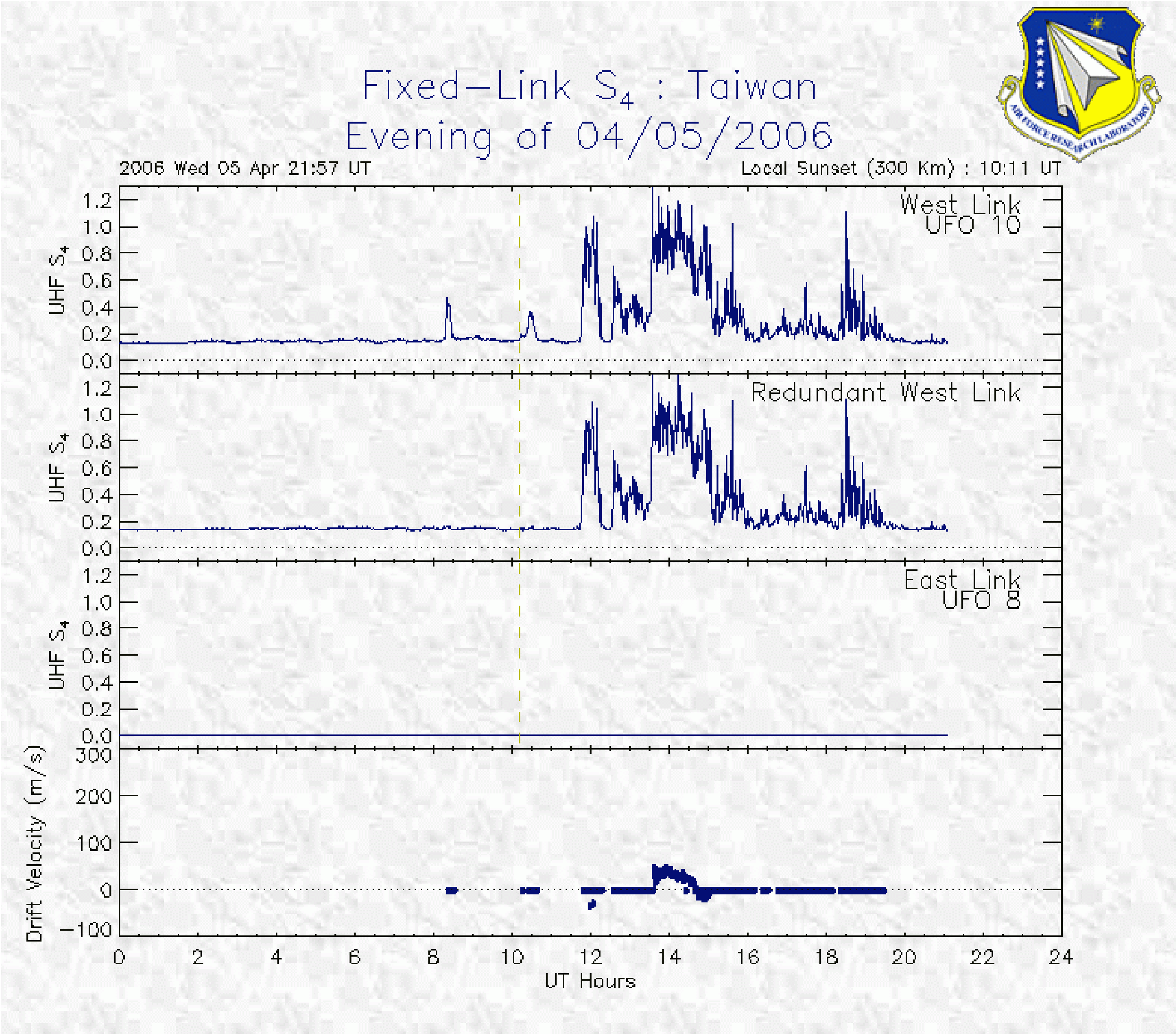


Fig. 4 Example of irregularity drift velocity observed on April 5, 2006

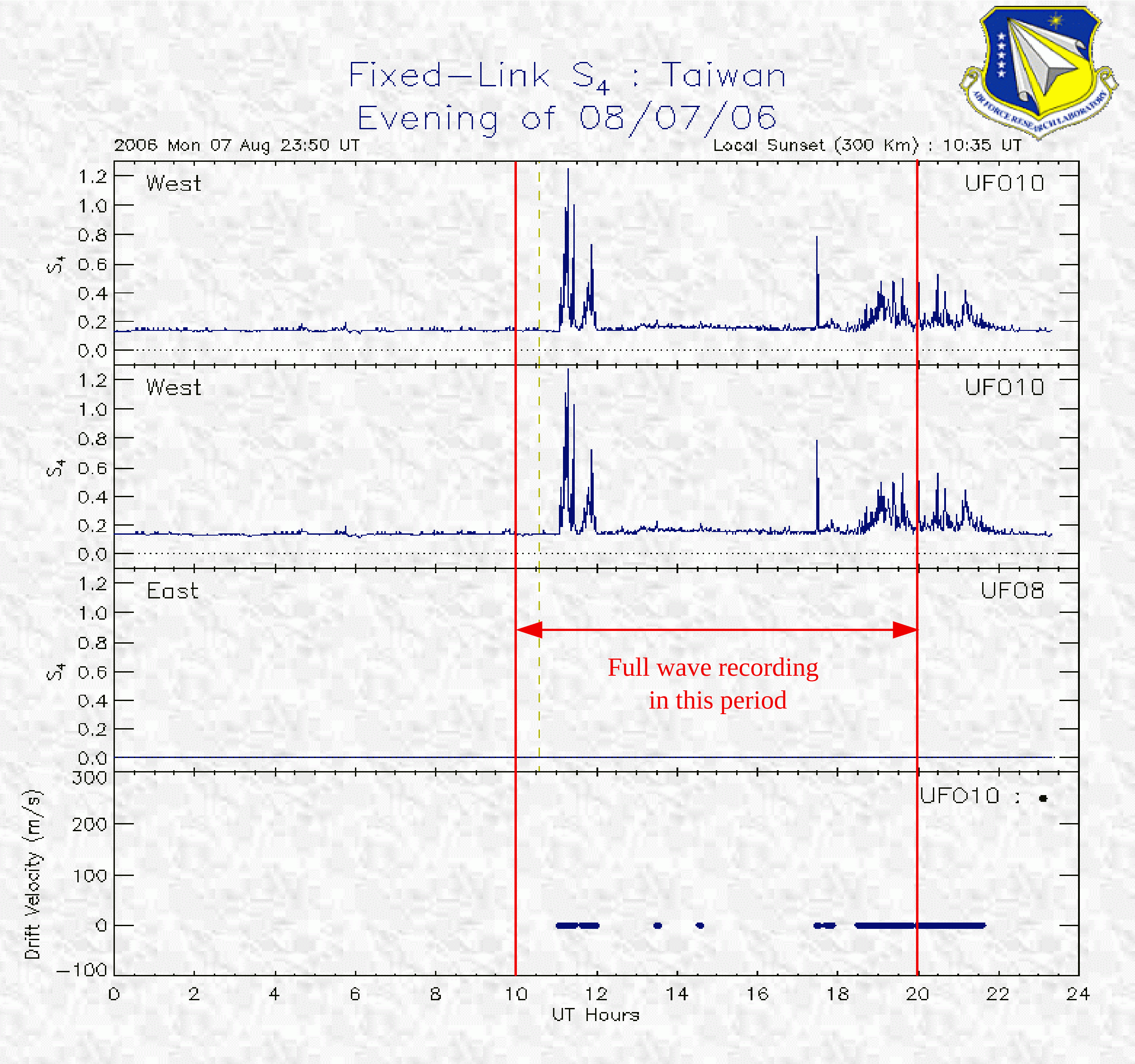


Fig. 5 No drift velocity indicated in this example

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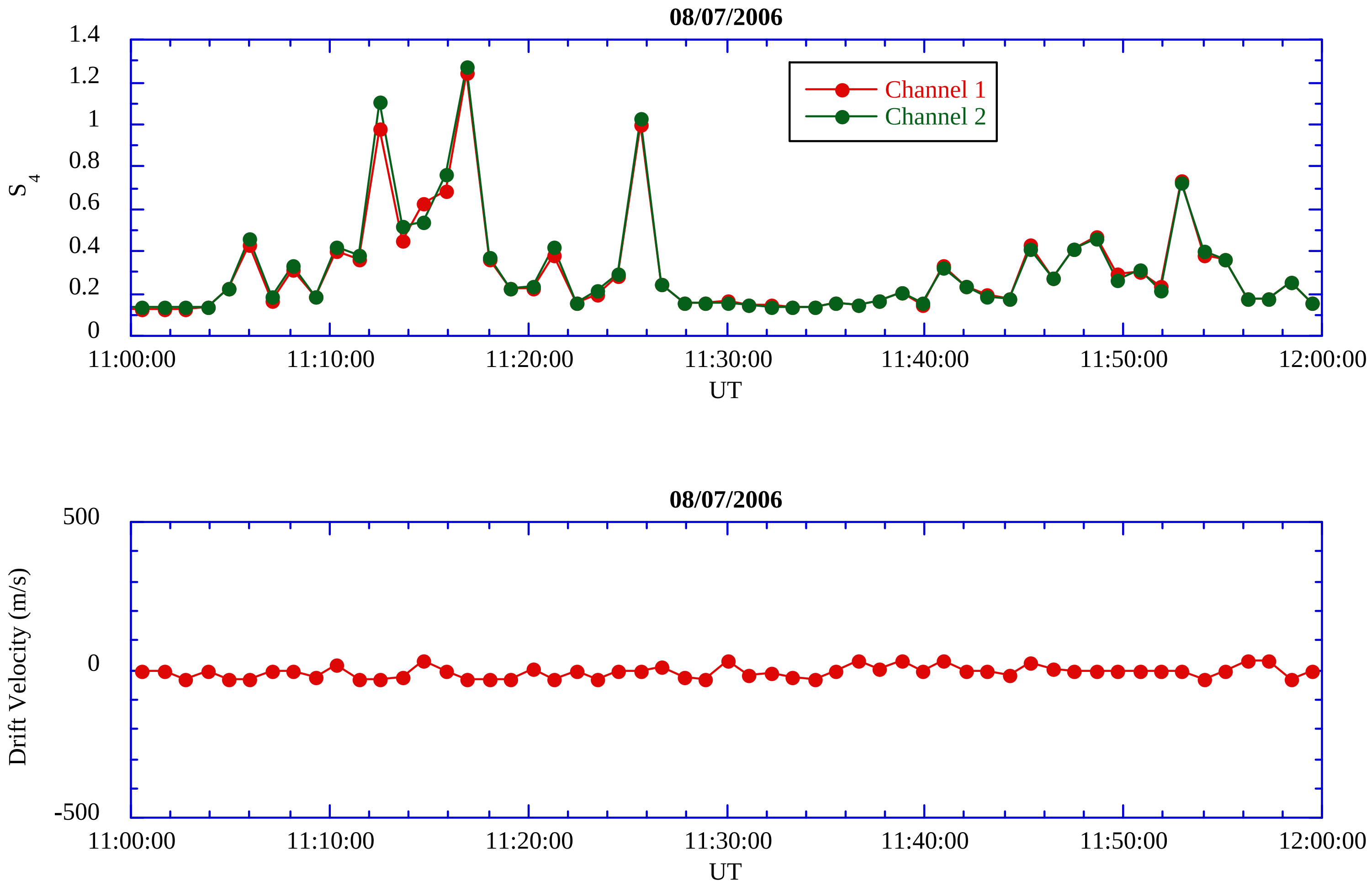

Fig. 6 Cross-correlation analysis of data in Fig. 5

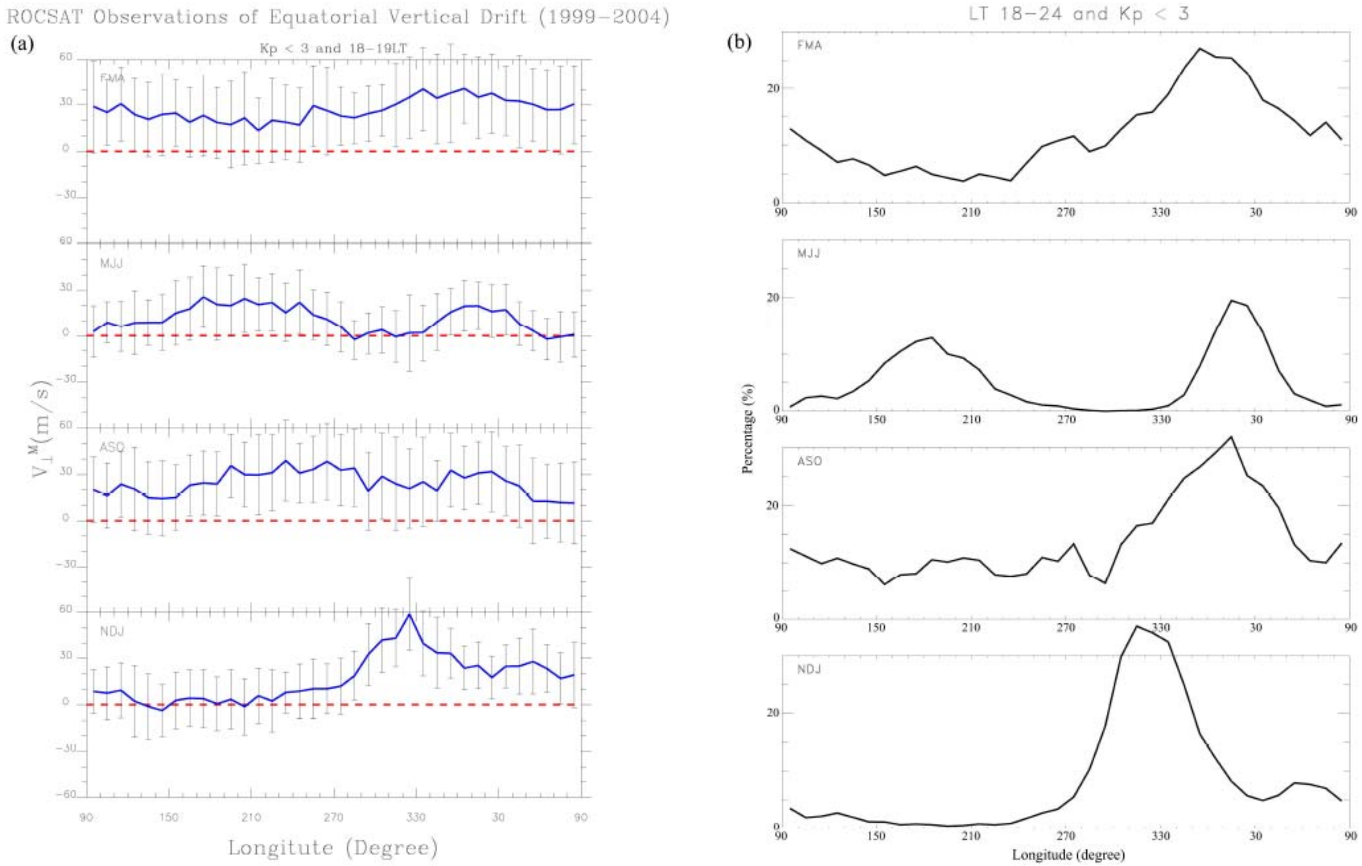

Fig. 7. (a) The s/l distribution of ROCSAT observations of topside ionospheric vertical drift velocities. (b) s/l distribution of topside ionospheric irregularity occurrence rates observed by ROCSAT before midnight and during quiet geomagnetic period.

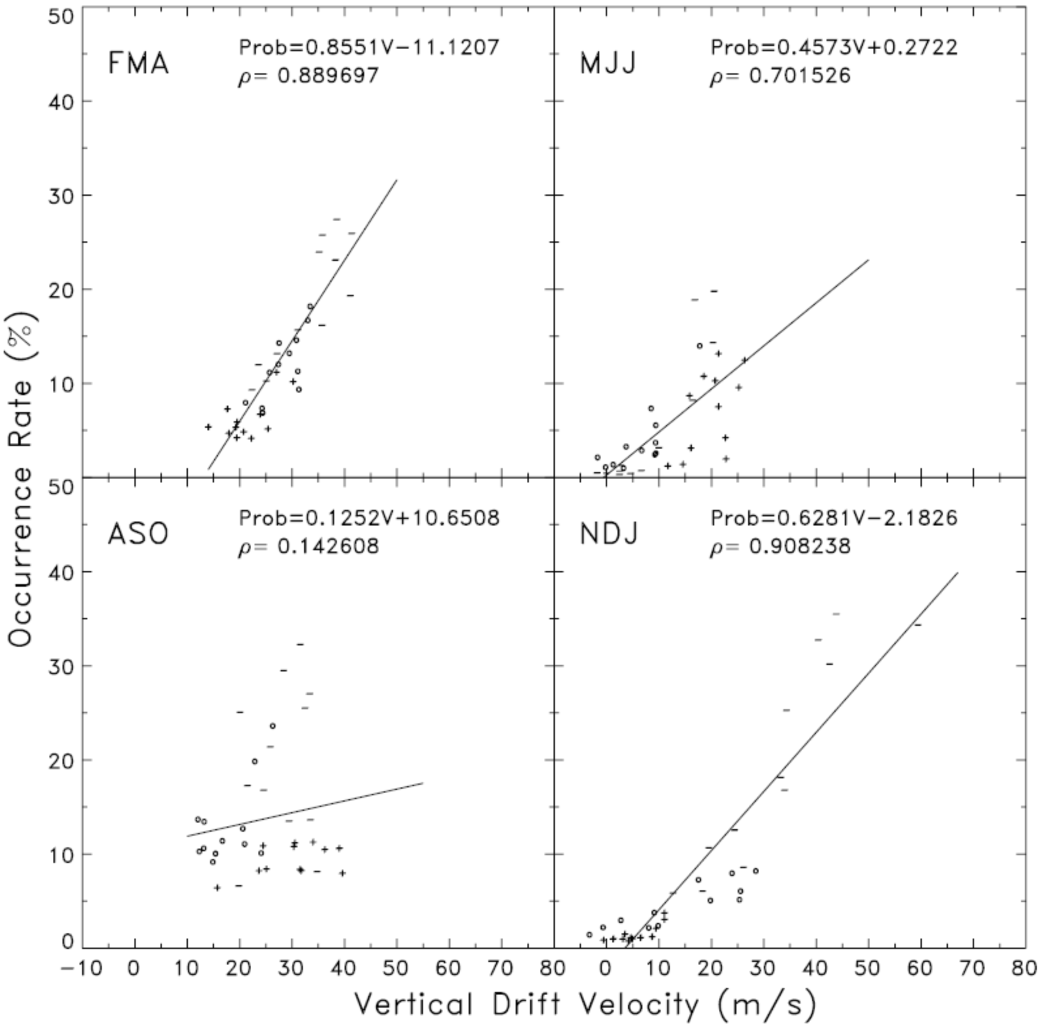

Fig. 8. Linear regression analysis of the topside vertical drift velocities from Fig. 7(a) with the irregularity occurrence rates from Fig. 7(b). Data points are labelled with 0, +, and – to identify data in the longitude regions of Figs. 7(a) and 7(b) in which the magnetic declination is around zero, positive, and negative, respective.

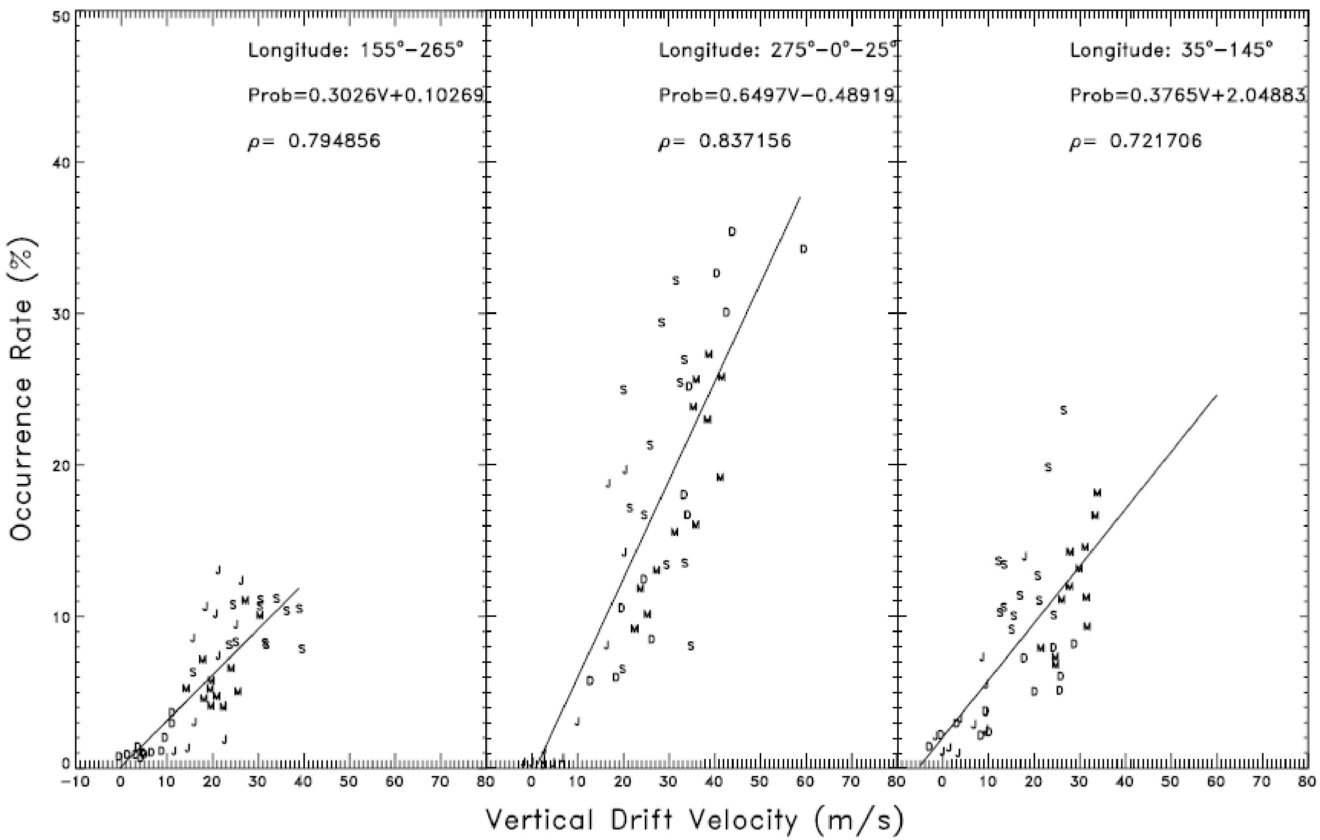

Fig. 9. Linear regression analysis of the topside vertical drift velocities with irregularity occurrence rates at longitude regions with three different magnetic declinations. Data points are labelled with the first alphabet to identify the month of observation.